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Theoretical approaches to particle propagation and acceleration in turbulent intergalactic medium

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Abstract. Intercluster medium is expected to be turbulent with turbulence being superAlfvenic at large scales. Magnetic fields substantially modify the turbulent cascade when the turbulence reaches the scales at which the fluctuation velocity gets less than the Alfven velocity. At those scales it is possible to consider three cascades, of fast, slow and Alfven modes with little energy exchange between them. As Alfvenic and slow modes are anisotropic they marginally scatter and accelerate cosmic rays, while fast modes dominate the processes. However, in the presence of cosmic rays the turbulence is modified as cosmic rays transfer the energy of compressible motions (i.e. slow and fast modes) from large scales to the scale of cosmic ray Larmor radius. This results in generation of a new small-scale Alfvenic component which is not a part of the ordinary MHD cascade. This component does scatter and accelerate cosmic rays. In addition, magnetic reconnection in turbulent medium accelerates cosmic rays. The complexity of the interacluster turbulence calls for observational studies. A new technique Velocity Coordinate Spectrum (VCS) is particularly promising for studies of velocity fluctuations with a new generation of X-ray observatories.

Key words: galaxies:clusters:general,turbulence, plasmas, intergalactic medium, galaxies: magnetic fields, MHD

1. Do we expect IGM to be turbulent?

A fluid of viscosity ν becomes turbulent when the rate of viscous dissipation, which is $\sim \nu/L^2$ at the energy injection scale L, is much smaller than the energy transfer rate $\sim V_L/L$, where V_L is the velocity dispersion at the scale L. The ratio of the two rates is the Reynolds number $Re = V_L L/\nu$. In general, when Re is larger than $Re_{crit} \sim 10-100$ the system becomes turbulent. Chaotic structures develop gradually as Re increases, and those with $Re \sim 10^3$ are appreciably less chaotic than those with $Re \sim 10^8$.

It is widely accepted that medium in clusters should be turbulent. Mergers of galactic subclusters may be one of the major energy injection mechanism (see Sarazin 2002, Brunetti 2003 and references therein). The details of the injection and the energy transfer are poorly understood. A crude picture includes the energy injection scale of 100-500 kpc and the injection velocity of the order of 10^3 km/s.

A difficulty that one faces trying to understand turbulence is clusters is that the diffusivity is very different along and perpendicular to magnetic field. This is related to the fact that the mean free path of ions is substantial. For *non-magnetized* intracluster gas the Re number is only marginally larger than Re_{crit} and therefore formally is only just sufficient for initiating the turbulence. At the same time, even small magnetization makes the Reynolds number for the motions perpendicular to magnetic field very large (e.g. more than 10^{10}). This poses the question of what a reasonable choice of the Reynolds number is for intracluster medium.

Strangely enough we do not have a good answer to this basic question. There are several processes that definitely influence the effective diffusivity of intracluster plasma. First of all, compressions of collisionless plasma should result in various instabilities that would decrease the mean free paths of protons. In addition, bending of magnetic field lines does not allow mean free path of protons to be larger than the scale at which the turbulent velocity is equal to the Alfven velocity (henceforth, the l_A scale). Therefore the effective Reynolds number at the injection scale will be $\sim 10^3$ for the field of 1 μG field, which is the field that fills according to Enslin et al. (2005) 90% of the intracluster volume.

Initially the turbulence is superAlfvenic and hydrodynamic motions easily bend magnetic field lines. Such turbulence is analogous to hydrodynamic one until the scales of the order of $l_A \equiv L(V_A/V_L)^3$ are reached. Assuming $V_L = 10^3$ km/s and $L = 100$ kpc we get 30 pc, if we adopt, following

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Ensslin et al (2005) that 1 μG field fills 90% of the ingracluster volume. The turbulence gets mangetohydrodynamic (MHD) for scales $l < l_A$ as magnetic fields control fluid motions. However, in both "hydrodynamic" and MHD regimes plasma effects continue to be important as they drain and redistribute energy of compressible motions (see Schekochihin et al. 2005).

2. What do we know about MHD turbulence?

There have long been understanding that the MHD turbulence is anisotropic (e.g. Shebalin et al. 1983). Substantial progress has been achieved by Goldreich & Sridhar (1995; hereafter GS95), who made an ingenious prediction regarding relative motions parallel and perpendicular to magnetic field **B** for incompressible MHD turbulence. An important observation that leads to understanding of the GS95 scaling is that magnetic field cannot prevent mixing motions of magnetic field lines if the motions are perpendicular to the magnetic field. Those motions will cause, however, waves that will propagate along magnetic field lines. If that is the case, the time scale of the wave-like motions along the field, i.e. $\sim l_{\|}/V_A$, ($l_{\|}$ is the characteristic size of the perturbation along the magnetic field and $V_A = B/\sqrt{4\pi\rho}$ is the local Alfven speed) will be equal to the hydrodynamic time-scale, $l_{\perp}/v_l$, where $l_{\perp}$ is the characteristic size of the perturbation perpendicular to the magnetic field. The mixing motions are hydrodynamic-like. They obey Kolmogorov scaling, $v_l \propto l_{\perp}^{1/3}$, because incompressible turbulence is assumed. Combining the two relations above we can get the GS95 anisotropy, $l_{\|} \propto l_{\perp}^{2/3}$ (or $k_{\|} \propto k_{\perp}^{2/3}$ in terms of wave-numbers). If we interpret $l_{\|}$ as the eddy size in the direction of the local magnetic field. and $l_{\perp}$ as that in the perpendicular directions, the relation implies that smaller eddies are more elongated. The latter is natural as it the energy in hydrodynamic motions decreases with the decrease of the scale. As the result it gets more and more difficult for feeble hydrodynamic motions to bend magnetic field lines.

GS95 predictions have been confirmed numerically (Cho & Vishniac 2000; Maron & Goldreich 2001; Cho, Lazarian & Vishniac 2002, 2003); they are in good agreement with observed and inferred astrophysical spectra (see Cho & Lazarian 2005). What happens in a compressible MHD? Does any part of GS95 model survives? The answer depends on the mode coupling. According to closure calculations (Bertoglio, Bataille, & Marion 2001; see also Zank & Matthaeus 1993), the energy in compressible modes in *hydrodynamic* turbulence scales as $\sim M_s^2$ if $M_s < 1$. Cho & Lazarian (henceforth CL03) conjectured that this relation can be extended to MHD turbulence if, instead of M_s^2, we use $\sim (\delta V)_A^2/(a^2 + V_A^2)$. (Hereinafter, we define $V_A \equiv B_0/\sqrt{4\pi\rho}$, where B_0 is the mean magnetic field strength.) However, since the Alfven modes are anisotropic, this formula may require an additional factor. The compressible modes are generated inside the so-called Goldreich-Sridhar cone, which takes up $\sim (\delta V)_A/V_A$ of the wave vector space. The ratio of compressible to Alfvenic energy inside this cone is the ratio given above. If the generated fast modes become isotropic (see below), the diffusion or, "isotropization" of the fast wave energy in the wave vector space increase their energy by a factor of $\sim V_A/(\delta V)_A$. This results in

$$\frac{\delta E_{comp}}{\delta E_{Alf}} \approx \frac{\delta V_A V_A}{V_A^2 + a^2}, \qquad (1)$$

which suggests that the drain of energy from Alfvenic modes is marginal along the cascade.

Our considerations above about the mode coupling can guide us in the discussion below. Indeed, if Alfven cascade evolves on its own, it is natural to assume that slow modes exhibit the GS95 scaling. Indeed, slow modes in gas pressure dominated environment (high β plasmas) are similar to the pseudo-Alfven modes in incompressible regime (see GS95; Lithwick & Goldreich 2001). The latter modes do follow the GS95 scaling. In magnetic pressure dominated environments or low β plasmas, slow modes are density perturbations propagating with the sound speed a parallel to the mean magnetic field. Those perturbations are essentially static for $a \ll V_A$. Therefore Alfvenic turbulence is expected to mix density perturbations as if they were passive scalar. This also induces the GS95 spectrum.

The fast waves in low β regime propagate at V_A irrespectively of the magnetic field direction. In high β regime, the properties of fast modes are similar, but the propagation speed is the sound speed a. Thus the mixing motions induced by Alfven waves should marginally affect the fast wave cascade. It is expected to be analogous to the acoustic wave cascade and hence be isotropic.

3. How does turbulence scatter and accelerate cosmic rays?

The propagation of cosmic rays (CRs) is affected by their interaction with magnetic field. This field is turbulent and therefore, the resonant interaction of cosmic rays with MHD turbulence has been discussed by many authors as the principal mechanism to scatter and isotropize cosmic rays. Although cosmic ray diffusion can happen while cosmic rays follow wandering magnetic fields (Jokipii 1966), the acceleration of cosmic rays requires efficient scattering. For instance, scattering of cosmic rays back into the shock is a vital component of the first order Fermi acceleration.

While most investigations are restricted to Alfvén modes propagating along an external magnetic field (the so-called slab model of Alfvénic turbulence) (see Schlickeiser 2002), obliquely propagating MHD modes have been included in Fisk et al. (1974) and later studies (see Pryadko & Petrosian 1999). A more complex models were obtained by combining the results of the Reduced MHD with parallel slab-like modes . Models that better correspond to the current understanding of MHD turbulence (see above) have been considered lately. Chandran (2000, henceforth C00) considered resonant scattering and acceleration by incompressible MHD turbulence. Resonant scattering and acceleration by the compressible MHD turbulence was considered in Yan & Lazarian (2002, 2004, henceforth YL02, YL04). There the following result was obtained for the diffusion coefficients that governed by Alfvenic scattering

$$\begin{bmatrix} D_{\mu\mu} \\ D_{pp} \end{bmatrix} = \frac{v^{2.5}\mu^{5.5}}{\Omega^{1.5}L^{2.5}(1-\mu^2)^{0.5}}\Gamma[6.5, k_{max}^{-\frac{2}{3}}k_{\parallel,res}L^{\frac{1}{3}}] \begin{bmatrix} 1 \\ m^2V_A^2 \end{bmatrix}, \tag{2}$$

where $\Gamma[a, z]$ is the incomplete gamma function. This result was obtained using a tensor of magnetic fluctuations that was obtained in the CLV02 study. It provides scattering and acceleration rates orders of magnitude larger than those in C00 for the most of energies considered. However, if energy is injected through random driving at large scale $L \gg k_{\parallel,res}^{-1}$ the scattering frequency,

$$\nu = 2D_{\mu\mu}/(1-\mu^2), \tag{3}$$

are still much smaller than the estimates for isotropic and slab model. What does scatter cosmic rays? Our work in YL02 identified fast modes as the principal agent responsible for CR scattering and acceleration. A study in YL04 showed that this is true in spite of the fact that fast modes are subjected to much more dissipation compared to the Alfven modes. In the next section we shall discussed another possibility proposed in Lazarian & Beresnyak (2006), namely, instabilities related to cosmic rays that inject Alfven modes at resonant scales (see §4). This possibility may provide a physical justification for the earlier calculations in Brunetti et al. (2004).

The work above was done in relation to galactic cosmic rays. However, the problem of MHD turbulence with CR is a general one. Therefore in a recent paper Cassano & Brunetti (2005) considered fast modes as the principal component of CR acceleration in galaxy clusters (see also Brunetti 2004). A further work in this direction is in Brunetti & Lazarian (2006).

Resonant acceleration (we include Transit-Time-Damping acceleration to this category) is not the only process by which magnetized turbulence accelerates CR. For instance, the acceleration of cosmic rays by the large scale compressible motions was described in the literature rather long time ago (see Ptuskin 1988). In this regime slow and fast diffusion limit exist. The slow limit corresponds to the rate of particle diffusion out of compressible eddies, which is slower than the evolution rate of the eddies. On the contrary, in the fast diffusion limit particles leave the eddies before they turnover. Large scale compressions associated with anisotropic slow modes were used to accelerate Solar Flare CR in Chandran (2003) who considered slow diffusion regime. Fast diffusion regime was used in Chandran & Maron (2004ab) in application to CR acceleration in galaxy clusters. A comprehensive study of these processes has been done in Cho & Lazarian (2006). We found, first of all, in slow diffusion limit the resonance scattering, that is a part and parcel of the slow diffusion process, is the dominant acceleration process. Then, we identified fast modes as the principal cause of non-resonant acceleration. In addition, we showed that weak turbulence (Galtier et al. 2005) may be important for cosmic ray acceleration in the fast diffusion limit.

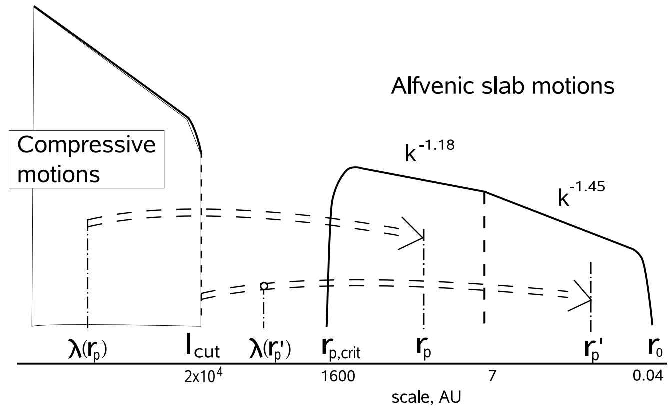

Fig. 1. Energy density of compressive modes and Alfvénic slab-type waves, induced by CRs, in galaxy clusters. The energy is transferred from the mean free path scale to the CR Larmor radius scale. If mean free path falls below compressive motions cutoff, spectrum of slab waves becomes steeper (from Lazarian & Beresnyak, 2006).

While the importance of fast modes for the scattering and the acceleration of CR is unquestionable, plasma and CR instabilities may make the actual turbulence in galaxy clusters more involved compared to a simple picture presented above. For instance, below we consider a robust CR instability that should modify the properties of MHD turbulence.

4. How can cosmic rays modify turbulence?

Studies of the backreaction of the energetic particles on the turbulence are usually limited by the damping of turbulence on energetic particles (see Brunetti & Blasi 2005, Ptuskin et al. 2005, Petrosian, Yan & Lazarian 2006). However, this is not the only effect of CR. For instance, Lazarian & Beresnyak (2006) have considered a transfer of turbulent energy to small (but not dissipation!) scales that is mediated by CR. As CR present a collisionless fluid, compressions CR through the compression of magnetic field preserve the adiabatic invariant $p_\perp^2/B$, where $p_\perp$ is the CR momentum perpendicular to magnetic field. CR with the anisotropic distribution of momenta, i.e. with nonzero $A = (p_\perp - p_\parallel)/p_\parallel$ are subjected to an instability, which growth rate can be estimated as

$$\Gamma_i(k_\parallel) = \omega_{pi}\frac{n_{CR}(p > m\Omega/k_\parallel)}{n}AQ, \tag{4}$$

where $\Omega = eB/mc$ is a cyclotron frequency, m – proton mass, n is the density of plasma, ω_{pi} is the ion plasma frequency, refering to n and $n_{CR}(p > m\Omega/k)$ is the number density of cosmic rays with momentum larger than minimal resonant momentum for a wavevector value of k. Q is a dimensionless numerical factor, depending only on cosmic ray power-law index α.

The outcome of this instability is the direct transfer of the energy from mean free path of a CR, which is determined by magnetic scattering of the CR, to the CR gyroradius. The magnetic perturbations at the gyroradius scale are the most efficient in CR scattering and this decreases the mean free path λ and therefore $A \sim v_\lambda/V_A$. At large scales the instability is limited by damping arising from the ambient Alfvenic turbulence ($r_{p,crit}$ in Fig. 1), while at small scales steepening limits the amplitude the perturbations. All in all, the interaction of CR with MHD turbulence results in an additional slab-like small-scale component of Alfvenic perturbations that interacts with CR much more efficiently than the Alfvenic mode being excited by the energy injection scale.

5. Can magnetic reconnection accelerate CR?

Magnetic reconnection is a process that we expect to happen routinely in magnetized turbulent fluid. This even more true for superAlfvenic turbulence when fluid motions bend magnetic fields easily. Indeed, magnetic reconnection should happen whenever magnetic field with non-parallel direction interact.

Several schemes of magnetic reconnection are known (see Fig. 2). The most famous one is the Sweet-Parker (Parker 1957, Sweet 1958) reconnection, which naturally occurs when magnetic fields get into contact over long current sheets. This is the most natural arangement of magnetic field to get into within the turbulent fluid as random moving flux tubes collide and push their way through one another. The scheme provide ridiculously low rates of reconnection to be of astrophysical importance, however. Indeed, the reconnection rate scales as $V_A Rm^{-1/2}$, where $Rm = V_A L/\eta_{mag}$ is the Lunquist number, which for realistic values of magnetic diffusivity η_{mag} is so humangous that any processing of magnetic energy via reconnection gets absolutely negligible for any astrophysical system (e.g. stars, interstellar medium) not to speak about intracluster medium with its much larger scales.

The Petcheck (1964) scheme emerged as an answer to the evidence of fast reconnection that cannot be explained within the Sweet-Parker model. Within this scheme the reconnection is concentrated along thin filaments from which oppositely directed magnetic field lines diverge. It is clear at this moment that it cannot be sustained at large R_L for smooth resistivities. Whether or not anomalous effects, e.g. those related to Hall term, can provide reconnection at rates comparable with the Alfvén speed is hotly debated[1] (see Biskamp, Schwarz & Drake 1997, Shay et al. 1998, Shay & Drake 1998, Bhattacharjee, Ma & Wang 2001). We feel, however, that the issue of satisfying boundary outflow conditions is the most controversial element in applying Petscheck scheme to astrophysical conditions. If very special global geometry or magnetic fluxes, e.g. convex magnetized regions, is required to enable reconnection, then for a generic astrophysical case the reconnection is slow (see Fig. 3).

The turbulent reconnection model proposed in Lazarian & Vishniac (1999, henceforth LV99) deals with magnetic

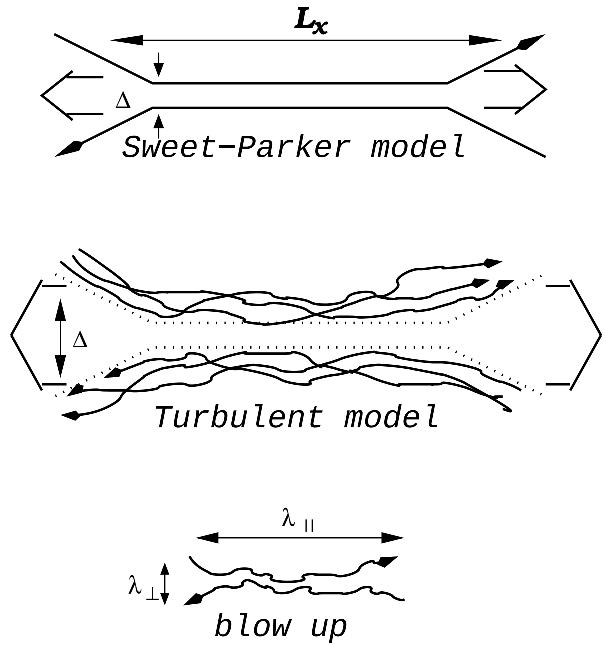

Fig. 2. *Upper plot*: Sweet-Parker model of reconnection. The outflow is limited by a thin slot Δ, which is determined by Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \Delta$. *Middle plot*: Turbulent reconnection model that accounts for the stochasticity of magnetic field lines. The outflow is limited by the diffusion of magnetic field lines, which depends on field line stochasticity. *Low plot*: An individual small scale reconnection region. The reconnection over small patches of magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches come together.

field configurations with flat long current sheets. However, these sheets consist of small sheets related to the interaction of individual turbulent elements of magnetic flux. The outflow within the model is limited not by the thickness of the current sheet, but by magnetic field wondering. As the result the rate of reconnection is proportional to the turbulence intensity. The model can explain flaring associated with reconnection as well as high rates of reconnection that are required by both observations and theory (e.g. dynamo theory). Calculations in Lazarian, Vishniac & Cho (2004) confirm main points of the LV99 model (e.g. the rate of field line wondering) and extend it to reconnection in partially ionized gas.

There are several ways how magnetic reconnection can accelerate cosmic rays. It is well known that electric fields in the current sheet can do the job. For Sweet-Parker reconnection this may be an important process in those exceptional instances when Sweet-Parker reconnection is fast in astrophysical settings. For Petscheck reconnection only an insubstantial part of magnetic energy is being released within the reconnection zone, while bulk of the energy is being released in shocks that support X-point. Therefore one would expect the shock acceleration of cosmic rays to accompany Petscheck reconnection.

Similarly to the Petscheck scheme the turbulent reconnection process assumes that only small segments of magnetic

[1] For instance, the necessary condition for the anomalous effects to be important, e.g. for that the electron mean free path is less than the current sheet thickness (see Trintchouk et al. 2003) is difficult to satisfy for the ISM, where the Sweet-Parker current sheet thickness is typically *much* larger than the ion Larmor radius.

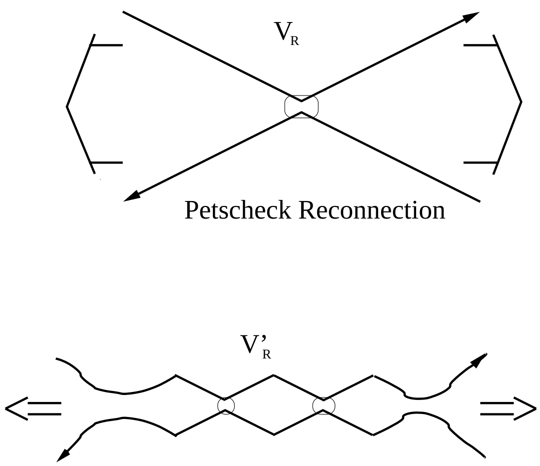

Fig. 3. *Upper plot*: Petscheck reconnection scheme has a magnetic diffusion region (rectangular area at the tip of the magnetic field line bending) for which both the longitudinal and transversal dimensions are determined by the Ohmic diffusivity. To enable $V_R \sim V_A$ the model requires field line opening over the whole astrophysical scale involved, which is difficult to satisfy in practice. *Lower plot*: External forcing, e.g. the forcing present in the ISM, is likely to close the opening required by the Petscheck model. In this case the global outflow constraint is not satisfied and the resulting reconnection speed is $V_R' \ll V_A$. As the result the Petscheck reconnection cannot operate steadily and therefore cannot deal with the amount of flux that, for instance, an astrophysical dynamo would require to reconnect.

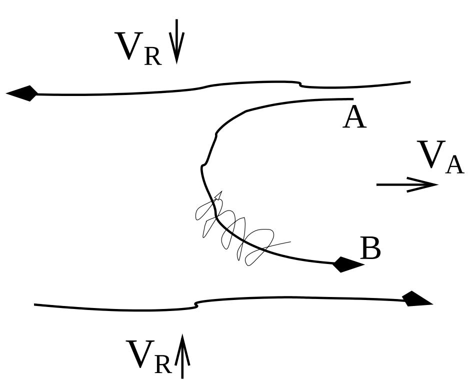

Fig. 4. Cosmic rays spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move towards each other with the reconnection velocity V_R. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of V_A. Bouncing at points A and B happens because either of streaming instability or turbulence in the reconnection region.

field lines enter the reconnection zone and are subjected to Ohmic annihilation. Thus only small fraction of magnetic energy, proportional to $R_L^{-2/5}$ (LV99), is released in the current sheets. The rest of the energy is released in the form of nonlinear Alfvén waves that are generated as reconnected magnetic field lines straighten up. Such waves are likely to cause second order Fermi acceleration. This idea was briefly discussed in Lazarian et al. (2001) in relation to particle acceleration during the gamma-ray burst events. In addition, large amplitude Alfvénic motions in low β, i.e. magnetically dominated, plasmas are likely to induce shocks (see Beresnyak, Lazarian & Cho 2005), which can also cause particle acceleration.

However, the most interesting process is the first-order Fermi acceleration that is intrinsic to the turbulent reconnection. To understand it consider a particle entrained on a reconnected magnetic field line (see Fig. 4). This particle may bounce back and force between magnetic mirrors formed by oppositely directed magnetic fluxes moving towards each other with the velocity V_R. Each of such bouncing will increase the energy of a particle in a way consistent with the requirements of the first-order Fermi process. The interesting property of this mechanism that potentially can be used to test observationally the idea is that the resulting spectrum is different from those arising from shocks. Gouveia Dal Pino & Lazarian (2003) used particle acceleration within turbulent reconnection regions to explain the synchrotron power-law spectrum arising from the flares of the microquasar GRS 1915+105. Note, that the mechanism acts in the Sweet-Parker scheme as well as in the scheme of turbulent reconnection. However, in the former the rates of reconnection and therefore the efficiency of acceleration are marginal in most cases.

6. How can we test the turbulence model?

There are several ways that information about turbulence in intracluster medium can be obtained from observations. For instance, magnetic power spectrum has been obtained using Faraday rotation (see Ensslin 2004, Ensslin, Vogt & Pfromer 2005). The issues of detectibility of velocity turbulence have been discussed in Sunyaev, Norman & Bryan (2003). Recent advances in the techniques of studies of turbulence via velocity fluctuations (see review by Lazarian 2004 and references therein) enable us to get spectra of turbulent fluctuations. The techniques described there can potentially separate compressible and incompressible motions. For instance, a Velocity Coordinate Spectrum (VCS) technique can be used to extract turbulence statistics from the Doppler-shifted spectra even when the measurements are made over a limited number of directions (even one) or the object is not resolved (Lazarian & Pogosyan 2006). Such measurements would already be possible, if not for the failure of the high velocity resolution instrument on board of the ASTRO-E2. An example of such a study that can be available with the forthcoming X-ray telescope Constellation X is presented in Fig. 5.

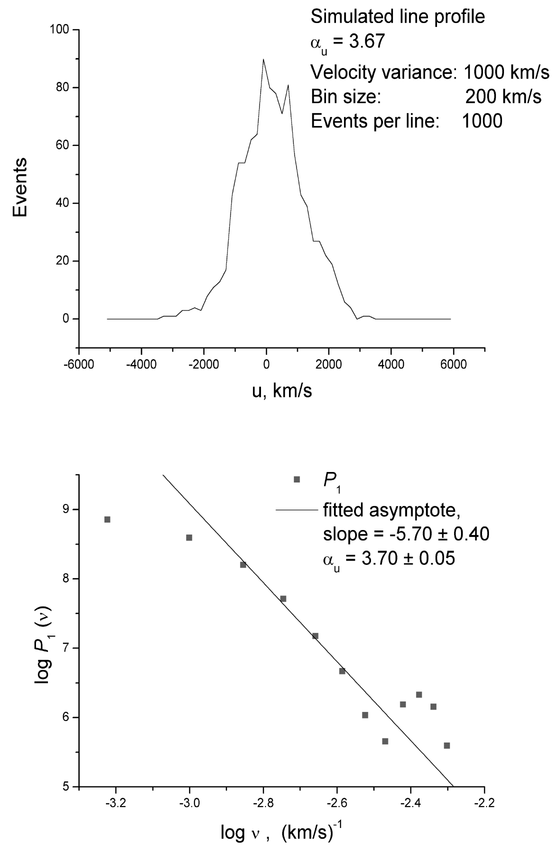

Fig. 5. An example of the velocity line profile (upper plot) and velocity spectrum (lower plot) for underlying Kolmogorov turbulence that can be produced with observations using Constellation X forthcoming X-ray facilty with 1 hour exposure (Chepurnov & Lazarian 2006).

7. What are the prospects of the field?

The detailed description of the CR acceleration and scattering is a challenging problem that requires coordinated efforts of both theorists and observers. It is clear that at the moment we do not have an adequate description of MHD turbulence in the collisionless fluid and this is an impediment for the progress. To get such a description one needs to account for different instabilities that affect magnetized collisionless intercluster plasmas. This, together with the change of effective Re fluid number as magnetic field and instabilities evolve, make the description of turbulence quite challenging. Together with turbulence driving the above processes determine the efficiency of the CR interaction with magnetized turbulence. We know by now that if the energy is injected at large scales, the interaction of CR of low energies with Alfvenic part of MHD cascade is suppressed. This, however, may not be true if some part of Alfven modes is generated by small scale plasma instabilities. In particular, some of these instabilities may be due to CR themselves. In addition, reconnection within chaotic fields may accelerate CR directly. Therefore, with more observational data, clusters of galaxies Nevertheless, with more observational data, clusters of galaxies may serve as a good testing ground for studies of the fundamental processes involving CR.

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